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Remote laser processing of composite materials with different opto – thermic properties

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Abstract

Near net shape preforms with a minimum of material consumption are required to increase the acceptance of fibre reinforced polymers in the industry, This should be accompanied with appropriate, fast and flexible processes. The $2^1/_2$ D beam deflection expands the area of possible kinds of processing strategies, wherefore the laser can be a tool for the future. The development of remote laser processing is strongly connected with the understanding of the interaction between tool and material. Within the paper investigations on opto – thermic properties of the components as a function of the wavelength of the beam source were shown. The results of the measurements are fundamental for processing composite structures made of glass- or carbon fibre and polymer matrices.

Keywords: laser; cutting; remote; glas or carbon fibre reinforced polymers; gfrp; cfrp

1. Motivation

A growing demand for high-strength composite components can be observed at different industries. The largest volumes are provided in the automotive-, aircraft- and wind power – industry, as well as machinery and plant engineering [1]. Here, the specific properties, for example the low thermal expansion coefficient of carbon fibres can be exploited. Such parts are used in textile machinery, which require maximum accuracies even under varying temperature conditions [1]. The main challenge in the field of composite materials is the improvement and optimization of existing production processes and procedures [2]. The developed process technologies have to guarantee a high reproducibility. For this purpose, a good knowledge of the complex interactions between material and laser beam is necessary. Within the paper investigations on opto – thermic

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properties as a function of the laser wavelength and material properties were shown. The results of the measurements are fundamental for processing of composite structures made of glass or carbon fibre and polymer matrices. Also the results will form the basis to implement the laser into production cycles which is shown at an example of a near net shape part.

2. Experimental

Basis of application of energy in laser material processing is the absorption of the electromagnetic waves. Absorption A results from reflectance R and transmittance T as to be seen in equation 1.

$$A = 1 - R - T \quad (1)$$

Uniform specimens were prepared to obtain comparable results of the opto-thermic behaviour. They are characterized by an unidirectional-layered structure. The specimens differ in thickness, matrix and reinforcement material as well as fibre volume content. Dimensions of the specimen are 40 x 40 mm. Density and fibre volume content are determined experimentally (Table 2).

NIR and IR spectroscopy measurements were planned to be used to evaluate parameters for absorption, transmittance and reflectance of the specimen. In the presented case, the direct determination of transmission by means of spectroscopic measurement methods had led to ambiguous conclusions. A highly diffuse transmittance occurs at the detector side of the specimen, which the embedded reinforcement material is responsible for. Here the measured values are not selective enough. For this reason, the spectroscopic studies are limited to the directed and diffuse reflectance.

Irradiating the specimen with beam sources of different wavelengths will carry out statements about transmittance. Also in this case, measurement of transmittance was not always significant. Therefore expanding the investigations by evaluating the surface temperatures of the specimens leads to a meaningful conclusion about absorption behaviour as a function of material properties.

2.1. Evaluating opto- thermic properties

Near infrared and infrared spectroscopy are rapid and non- destructive methods to characterize reflectance and transmittance. Illuminating the surfaces of the specimen and collecting sufficient scattered radiation with ellipsoids can record spectra of rough surfaces. Due to the thickness of the specimen, statements about transmittance are not possible. However spectroscopy provides information about reflectance as a function of material property variations. The investigations were carried out with a “Bruker Vertex 70” measurement device for near infrared radiation and a “Perkin Elmer 2000” device for infrared radiation. Subsequently the principles of measurements are shown in Fig. 1.

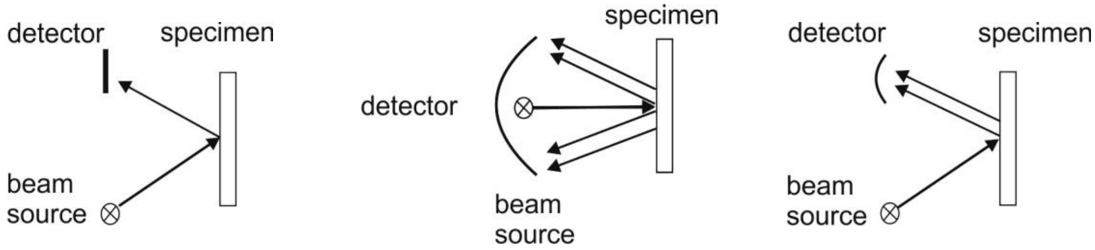


Fig. 1. Principle of measurement: direct reflectance (left); diffuse reflectance Bruker Vertex 70 (λ= 1.09 µm) (center); diffuse reflectance Perkin Elmer Spectrum 2000* (λ= 10.6 µm) (right)

A complete evaluation of the absorption behaviour of the specimen is not possible using only infrared and near-infrared spectroscopy. Therefore an experimental set up, consisting beam sources of different wavelengths, power meter and a non-contact temperature measurement device was build up (Fig. 2) (Table 1). The carried out measurements will evaluate the influence of different wavelengths as a function of material property variations. In order to provide comparable test conditions the spot diameter was set to 5 mm to adjust similar intensities on the specimen surface. In combination with non-contact temperature measurements the absorption can be estimated for certain material thicknesses. The specimens were irradiated for 120 sec with a power of 0.5 W in order to prevent damage of the matrix material.

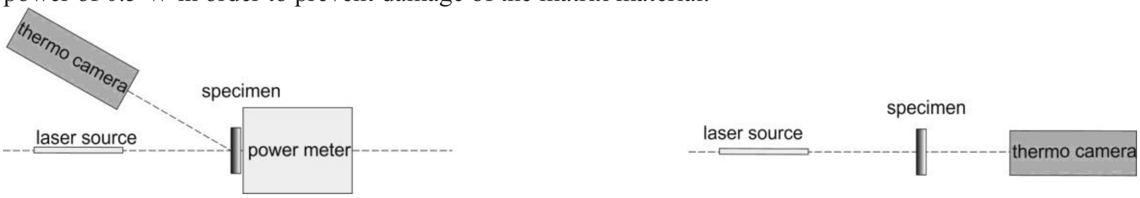


Fig. 2. Experimental setup: transmission and non-contact temperature measurement at the front side (left) non-contact measurement at the back side (right)

Table 1. Experimental equipment

Component	Name	Properties
Beam source NIR	SP 25	25 W, M^2< 1,1
Beam source IR	Serie 48-1	10 W, M^2<1,2
Thermo camera	TIM Connect	382 x 288 px
Power meter	UP 19 H9	Ø = 19 mm.

Composite materials provide an anisotropic material behaviour in the field of opto – thermic properties (Table 2). Influences are the fibre volume content, the reinforcement fibres and the matrix material. To examine the heat conductivity of the material with scattered fibre orientation it is important to know, that there is a parallel circuit along the fibre orientation and a series circuit across the fibre orientation. The properties arise from the rule of mixture [3].

* Detector size: $^1/_8$ of sphere

$$\lambda_{II} = \lambda_f \cdot \varphi + \lambda_m \cdot (1-\varphi) \tag{2}$$

$$\frac{1}{\lambda_\perp} = \frac{1}{\lambda_f} \cdot \varphi + \frac{1}{\lambda_m} \cdot (1-\varphi) \tag{3}$$

When determining the specific thermal capacity the rule of mixture has to be used [3].

$$c_{pUD} = \frac{c_f \cdot \rho_f \cdot \varphi + c_m \cdot \rho_m \cdot (1-\varphi)}{\rho_f \cdot \varphi + \rho_m \cdot (1-\varphi)} \tag{4}$$

Table 2. Specific properties GF, CF, PP, EP, GF PP, CF EP [4]

Material	Fibre volume content φ [%]	Thermal heat conductivity λ_{II} [W/m*K]	Thermal heat conductivity $\lambda_\perp$ [W/m*K]	Specific heat capacity c_p [J/Kg*K]	Density ρ [kg/m^3]
GF		1		764	2600
CF		17	1.4	710	1770
PP		0.2		1800	910
EP		0.2		1400	1200
GP PP	40	0.6	0.4	527	1919
GF PP	50	0.6	0.4	565	1722
GF PP	55	0.7	0.4	594	1821
GF PP	60	0.7	0.4	616	1881
GF EP	40	0.6	0.3	527	1919
GF EP	50	0.5	0.3	465	1785
CF EP	46	4.5	0.3	427	1484
CF EP	57	5.5	0.4	503	1517

3. Results and Discussion

3.1. Opto- thermic properties

When directly irradiating at the wavelength of 10.6 µm the values are almost at the same low level and independent from the matrix- and fibre material as well as the fibre volume content (Fig. 3). It may be expected, that the beam is reflected diffuse at the surface of the specimen, which is characterized by a top layer of matrix material with a thickness of approximately 14 µm (Fig. 5). In contrast, irradiating the specimen at the wavelength of 1.09 µm leads to a direct reflectance, which depending on the specimen thickness and percentage of reinforcement material (Fig. 3). Certainly only a mean ratio could be observed. It is assumed that the reflection occurs on the irradiated and non-irradiated surface of the specimen. The decrease of direct reflectance, depending on the thickness of the specimen can be explained by the grade of transmittance. The beam, which is reflected at the non-irradiated side, is transmitted twice trough the specimen. When irradiating a fibre-reinforced specimen with a wavelength of 1.09 µm, the direct reflectance is low. That leads to the assumption that a diffuse reflectance occurs on the fibre-generated surface (Fig. 4, Fig. 5).

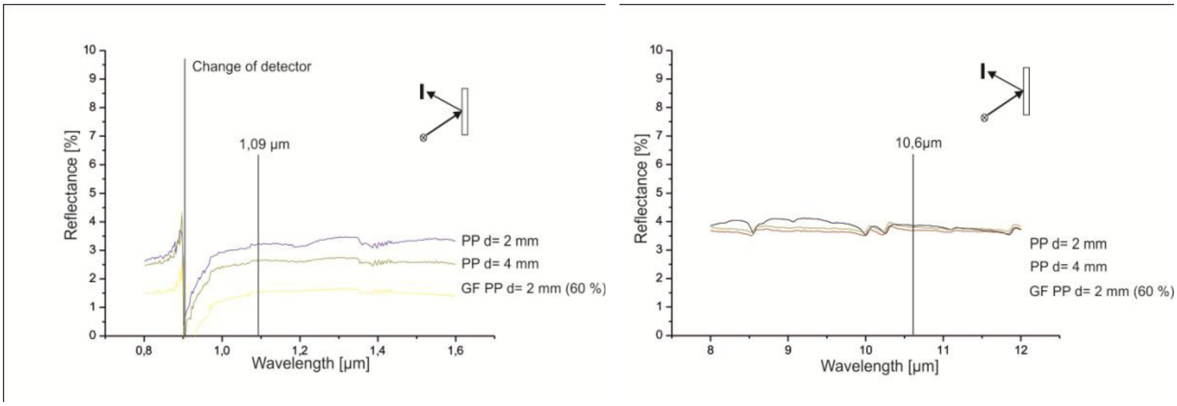
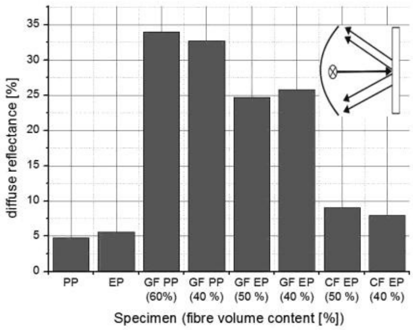


Fig. 3. Direct reflectance; near infrared radiation (λ= 1.09 µm) (left); infrared radiation (λ= 10.6 µm) (right)

The influence of the fibre volume content as well as of the material on diffuse reflectance can be observed in Fig. 4. High fibre volume contents are characterised by a raising packing fraction of fibres. As a result the effective surface of the fibres rises, which can be responsible for variation of the values (Fig. 4, Fig. 5, Fig. 6).

Irradiating the specimen at a wavelength of 10.6 µm leads to those values, which are mostly independent from material properties (Fig. 4). Hereby no significant dependence about absorption behaviour as a function of material properties could be found. A high transmittance through the matrix top layer (Fig. 5) is supposed, when irradiating the specimen at the wavelength of 1.09 µm. Hence the diffuse reflectance is caused by the surface generated by the fibre material (Fig. 5). The huge difference of values between the different reinforcement materials supports this assumption (Fig. 4). Low values of diffuse reflectance of carbon fibre reinforced specimen were determined when irradiating at a wavelength of 1.09 µm. Regarding low diffuse and direct reflectance in combination with high surface temperatures of irradiated specimen (Fig. 8) leads to the assumption of a high absorption in the carbon fibre reinforcement material.



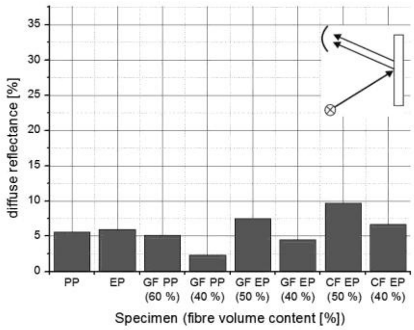


Fig. 4. Diffuse reflectance: near infrared radiation (λ= 1.09 µm) (left); infrared radiation (λ= 10.6 µm) (right)

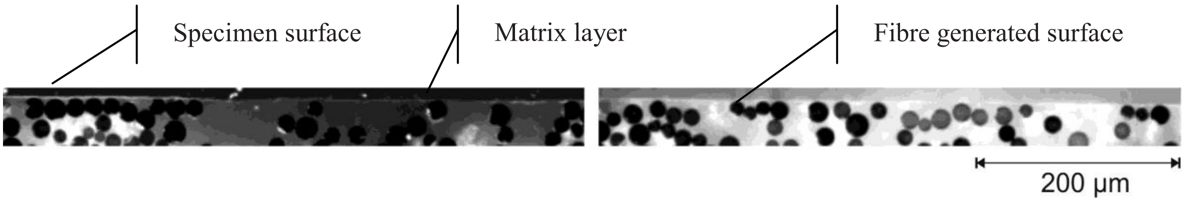


Fig. 5 Cross sections of the specimen surface; 40 % fibre volume content (left); 60 % fibre volume content (right) (GF PP)

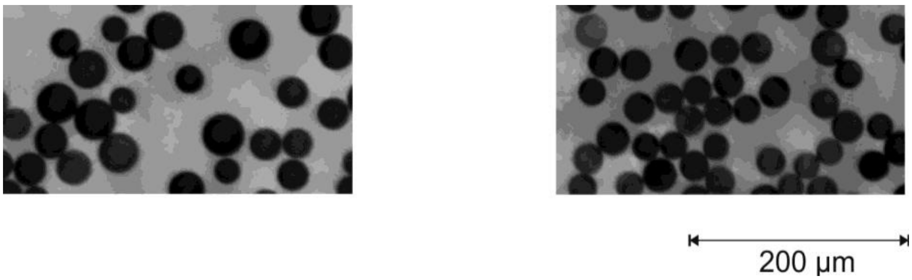


Fig. 6. Cross sections of fibre and matrix allocation; 40 % fibre volume content (left); 60 % fibre volume content (right) (GF PP)

However, the measuring principles of spectroscopy in spectra of infrared and near infrared radiation are different (Fig. 1), so that the results can be compared with each other only insufficiently. Therefore the influence of different wavelengths as a function of material property variation has to be examined by irradiating the specimen with laser beam sources of different wavelengths. Drawing conclusions of the absorption behaviour is made possible by determining the surface temperature of the irradiated side of the specimens and appointing a correlation between reflectance and transmitted laser power. Fig. 7 shows the dependence of transmitted power, depending on the fibre volume content, when irradiating glass- and carbon fibre reinforced polymers at a wavelengths 1.09 µm and 10,6 µm. The high value of transmitted power at a wavelength of 1.09 µm in combination with measured diffuse reflectance leads to a minimized absorption. Hence the measured surface temperature is low (Fig. 8). When irradiating carbon fibre reinforced polymers at a wavelength of 1.09 µm, a very low value of transmitted laser power was measured. Accordingly higher values of surface temperature appeared. In combination with low amounts of direct reflectance a high absorption is assumed. Certainly the recorded temperatures are overlaid by the thermal heat conductivity along the carbon fibre orientation. Irradiating specimen at a wavelength of 10.6 µm leads to very low values of transmitted laser power (Fig. 7). Due to the mean resolution of measured values, conclusions about transmitted laser power, as a function of material properties are not possible.

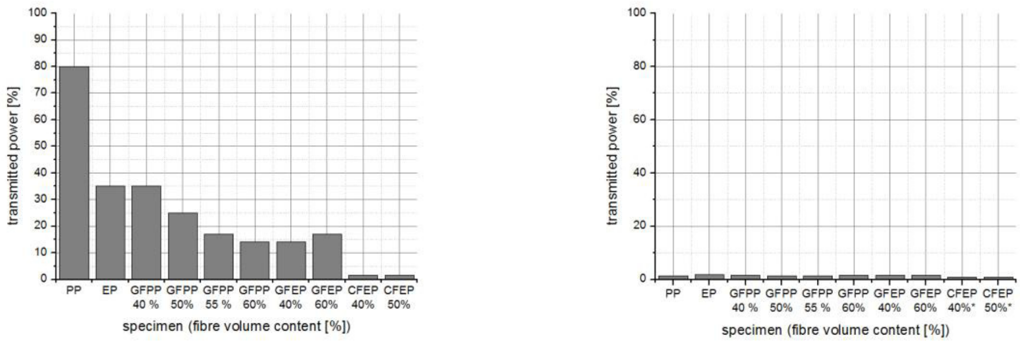


Fig. 7. Transmitted laser power depending on fibre volume content
Laser power: 0.5W; material: PP, EP, GFPP, GFEP, CFEP; specimen thickness d= 2 mm, *d=0.8 mm: (left) 1.09 µm; (right) 10.6 µm

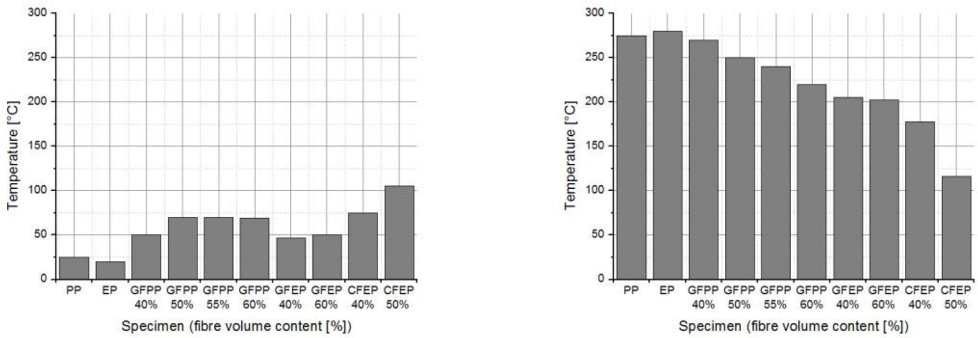


Fig. 8. Measured surface temperature depending on fibre volume content
Laser power: 0.5W; material: PP, EP, GFPP, GFEP, CFEP; specimen thickness d= 2 mm: (left) 1,09 µm; (right) 10,6 µm

When irradiating the specimen with a wavelength of 10.6 µm, high surface temperatures occurred and low values of transmitted power could be measured. The low amount of diffuse reflectance (Fig. 4) in combination with high surface temperatures leads to a high absorption of laser power in the specimen. This absorption both takes place in the matrix material as well as in the reinforcement material. However, the measured surface temperature is overlaid by the thermal heat conductivity of the reinforcement material. Carbon fibre is characterized by a huge rate of thermal heat conductivity (Table 2). Wherefore a major ratio of thermal energy is removed from the measuring zone in direction of fibre orientation. This effect also occurs when irradiating glass fibre reinforced polymers, but can be seen as symmetrically (Fig. 9). Specimens with high fibre volume content are characterized by a higher number of filaments, than specimen with low fibre volume content.

Hence a higher number of filaments can take part in heat conductance, which leads to a decreasing surface temperature.

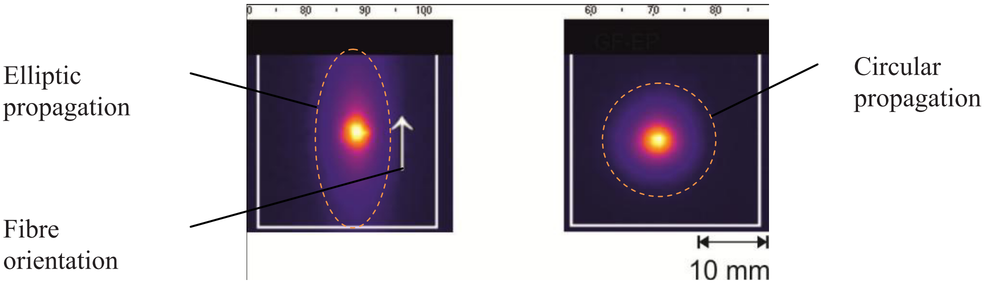


Fig. 9. Thermografic image of heat propagation depending on fibre orientation on the specimen surface, (left) carbon fibre reinforced polymer, (right) glass fibre reinforced polymer

3.2. Remote processing of near-net-shape constructions

The presented investigations are fundamental for the following development of applications. The measurements show that a CO_2 Laser at a wavelength of 10.6 µm is regarded as suitable. Processing of fibre-reinforced polymers is made possible by high-speed beam deflection systems. A fast mirror system based on galvanometer scanners is used to rapidly project the laser beam onto the material. Feed rates up to 20 m/s are possible and minimize the interaction time between laser and material. Thereby the heat-affected zone can be set to a minimum [5]. Laser remote cutting of a fibre reinforced polymer means a cyclic ablation until the cutting kerf is formed completely. The effective velocity is determined by the ratio between feed rate and needed ablation cycles. As an execution example, the processing of a lightweight spacer structure is presented in this study. This component is based on woven or knitted preforms, produced from commingled hybrid yarns. The components are glass fibre and polypropylene with a fibre volume content of 50 %. Furthermore it is characterized by multi-layer constructions (Fig. 10- 1, Fig. 10- 3) and cross-links in production direction (Fig. 10-2)

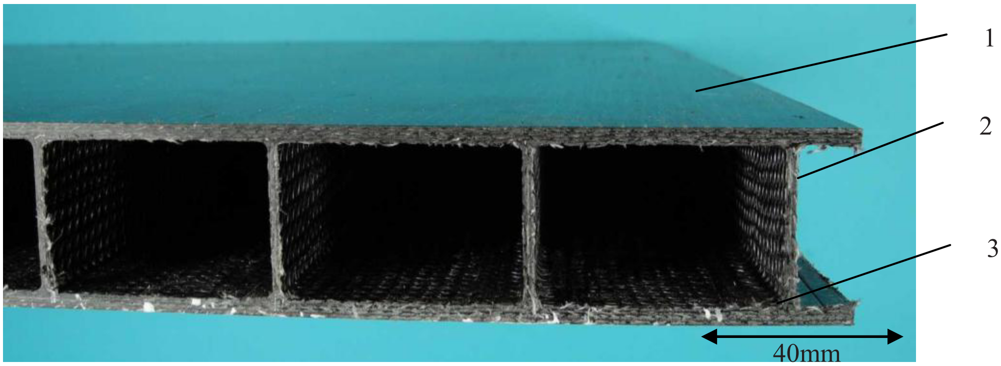


Fig. 10. Consolidated spacer structures

The processing of the presented lightweight spacer structure (Fig. 10) was made possible by $2^1/_2$ D beam deflection. In a first step, the upper layer (Fig. 10- 1) was cyclic ablated. Subsequently a focal adjustment was performed to ablate the lower layer (Fig. 10- 3). Comparing those results to state of the art milling or water jet cutting, the laser remote process is a force-free and low-wear treatment. Also a one-sided machining without repositioning of the work piece is a benefit. Furthermore cutting contours can be programmed, which include thru-cuts (Fig. 11- 1, - 4, - 5) as well as one-layer cuts with flexible geometries (Fig. 11- 2, - 3).

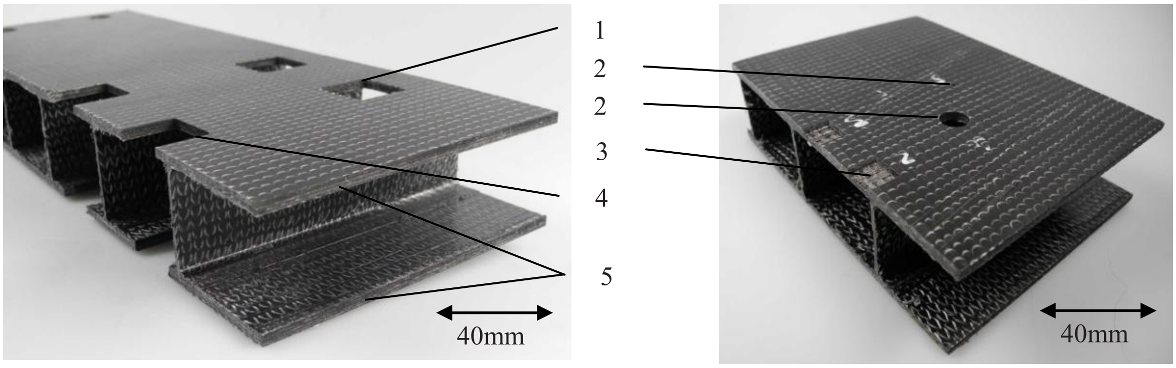


Fig. 11. Consolidated spacer structures with thru-cuts and single layer cuts

4. Conclusions

Laser processing of materials, which consist of two or more components with different opto - thermic properties, is accompanied with the knowledge of material behavior. Therefore the absorption characteristics of polymers and fibre-reinforced polymers were estimated. A correlation between material properties and reflectance, transmittance as well as absorption could be found. Further investigations have to minimize the overlaying thermal heat conductivity. The presented investigations are fundamental for processing of lightweight spacer structures. With the development of structurally optimized topologies of fibre-reinforced polymers the geometric complexity of components, preforms and blanks increases. Water jet processes as well as milling or drilling processes show limitations with respect to lifetime and flexibility. Therefore laser processing could be a tool to be up to the raising requirements of fibre reinforced polymers.

5. Acknowledgement

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Nomenclature	
NIR	Near infrared
IR	Infrared
GF	Glass fibre
CF	Carbon fibre
EP	Epoxy resin
PP	Polypropylene
GF PP	Glass fibre/ polypropylene composite
GF EP	Glass fibre/ epoxy resin composite
CF EP	Carbon fibre/ epoxy resin composite
A	Absorption
R	Reflectance
T	Transmittance
λ_{II}	Thermal heat conductivity along fibre orientation [W/m*K]
$\lambda_{\perp}$	Thermal heat conductivity across fibre orientation [W/m*K]
λ_m	Thermal heat conductivity of matrix material [W/m*K]
λ_f	Thermal heat conductivity of fibre material [W/m*K]
φ	Fibre volume content [%]
c_f	Thermal capacity of fibre material [J/kg*K]
c_m	Thermal capacity of matrix material [J/kg*K]
ρ_f	Density of fibre material [kg/m³]
ρ_m	Density of matrix material [kg/m³]